# Adriatic Circulation Experiment- Mesoscale Dynamics and Response to Strong Atmospheric Forcing

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## LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Processes governing exchanges between the shelf and deep ocean.
- Strongly forced mesoscale dynamics.
- Processes that communicate atmospheric forcing to the ocean interior.
- Use of dynamical understanding to improve performance of shallow water analysis products.

## OBJECTIVES

We seek to understand the role played by three primary driving forces: (1) wintertime Bora winds, (2) weaker, along-basin Sirocco winds and (3) seasonal buoyancy input from the Po River and other sources, in governing the evolution of coastal filaments, eddies and fronts in the northern Adriatic. Additional efforts will focus on the dynamics of watermass formation and subduction in a shallow sea regime.

## APPROACH

Winter and spring cruises studied the evolution of selected fronts and filaments under two distinctly different regimes of background stratification, riverine input and wind forcing. During February 2003 the northern basin (with the exception of the Po-influenced region along the Italian coast) was largely unstratified. Po discharge was weak (Fig. 1) and strong Bora wind events (Fig. 2) provided the dominant forcing. These cold air outbreaks typically had lateral scales of O(10 km) and durations of 1-2 days, driving the northern and central basin through intense, laterally sheared wind stress and large net surface heat loss. Although the May cruise was timed to sample the spring freshette, when Po outflow reaches its annual peak, discharge rates were anomalously weak (over one standard deviation below the 12-year mean) and provided only weak buoyancy forcing to the northern basin (Fig. 1). Both cruises followed an adaptive sampling strategy, using remotely sensed sea surface temperature (SST) and ocean color images to select energetic fronts and filaments. We used dedicated short-term meteorological forecasts to coordinate survey timing with atmospheric events, ensuring that target features were sampled during the periods of strong forcing. The observational program employed a towed, undulating sensor platform (TriSoarus, a hybrid SeaSoar vehicle) to conduct high-resolution,

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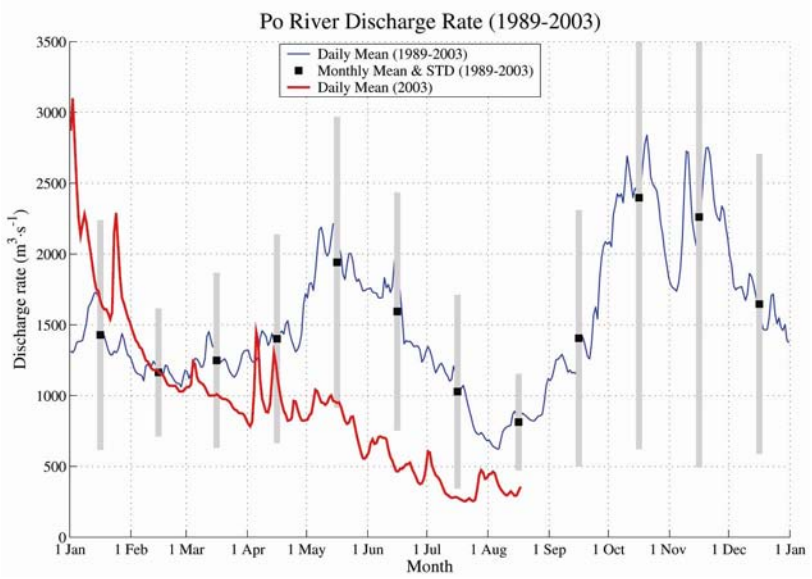


***Figure 1. Po River discharge rates. The blue line marks 1989 – 2003 climatological discharge, with squares indicating monthly averages and bars marking one standard deviation. The red line indicates monthly average discharge for the first half of 2003.***

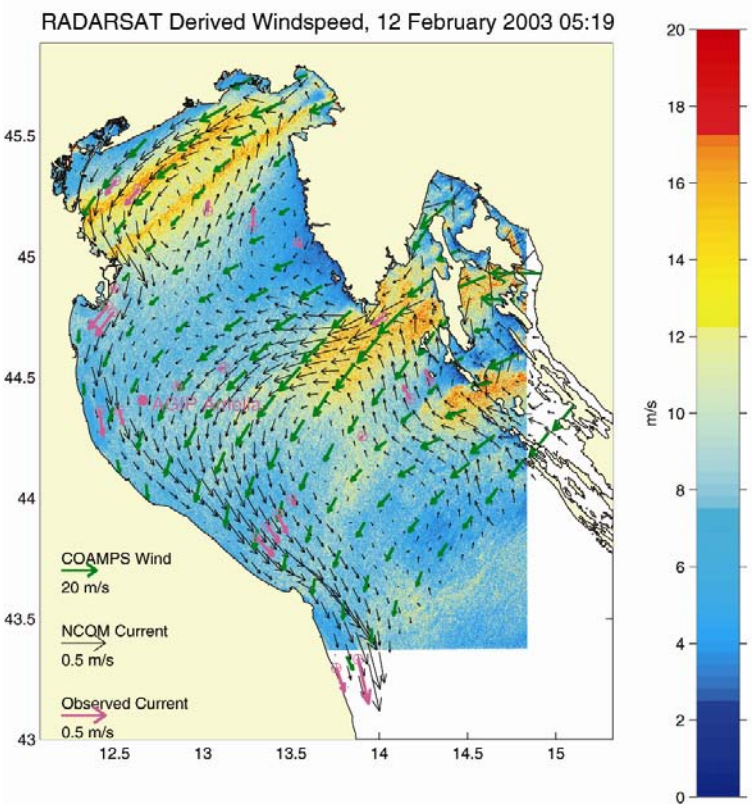


***Figure 2. (from Lee et al., 2005) RADARSAT wind speed (color) on 12 February with 48-hour average (12 -14 February) COAMPS wind vectors (black), near-surface (5 m) NCOM currents (green) and measured currents (magenta). A magenta circle marks the AGIP Amelia platform. The 4 km (1 km) COAMPS (NCOM) vectors are shown at 16 km (6 km) intervals for clarity. Large scale Bora winds from the northeast are intensified by coastal topographic gaps into sea surface wind jets that can extend across most of the Adriatic.***

three-dimensional surveys of physical and optical variability. Measurements conducted during the two cruises included:

- Continuous underway measurements of ocean currents (150 KHz Broadband Acoustic Doppler Current Profiler (ADCP)) and meteorological variables.
- Towed, undulating profiler measurements of temperature, salinity, chlorophyll and DOM Fluorescence, 660 nm beam attenuation, dissolved oxygen, nine-channel absorption and attenuation (AC-9) and currents (1200 KHz Broadband ADCP). TriSoarus typically profiled from 1-2 m depth to within 5 m of the bottom at tow speeds of 7-8 knots. Typical along track resolution was approximately 150 m (1500 m) at minimum (maximum) profiling depths of 15 m (200 m), with cross-track distances of 3-5 km.
- Optical profiling sampling temperature, salinity, chlorophyll and DOM fluorescence, 660 nm beam attenuation, spectral optical backscatter (Hydroscat), nine-channel absorption and attenuation (AC-9) and upwelling and downwelling irradiance. (B. Jones, USC)
- CTD/rosette casts sampling temperature, salinity, dissolved oxygen, chlorophyll fluorescence, 660 nm beam attenuation, nutrients and pigments. (B. Jones, USC, M. Marini, IRPEM)
- Plankton sampling using vertical net tows and rosette water samples. (D. Vilicic, U. Zagreb)
- Surface drifter deployments coordinated with the intensive towed surveys. (P. Poulain, OGS-Trieste)
- Microstructure profiles and time series of velocity profiles (5-beam bottom-moored ADCP). (H. Peters, U. Miami)
- Real time access to AVHRR and ocean color remote sensing (R. Arnone, NRL-SSC)
- Customized synoptic meteorological forecasts (D. Thaler, Austrian Military Weather Service and V. Tutis, Croatian Meteorological Service)

Efforts to develop a new Adriatic climatology complement the measurement program and provide opportunities to explore new techniques for characterizing regions dominated by short time- and space-scale variability. This alternative climatology organizes archived data by dynamical regime rather than the more typical time (e.g. monthly or seasonal) averaging. Because strong wind outbreaks and Po River discharge govern the dynamics of the northern and central Adriatic, we pursue canonical descriptions of Bora, Sirocco and 'low-wind' regimes under both weak and strong Po outflow. These descriptions will be further refined to account for seasonal variability in background stratification. The resulting dynamics-based climatological fields can be evaluated against both the measurements collected during our field program and individual 'snapshots' taken from the historical data. We also plan to evaluate these techniques using the extensive synthetic data sets generated by the NRL (Pullen) and Dartmouth (Cushman-Roisin) numerical efforts.

## WORK COMPLETED

Two cruises (winter and spring 2003) investigated strongly forced small- and meso-scale dynamics in the Northern and Central Adriatic Sea. In addition to our extensive towed profiling surveys, a team of U.S., Croatian and Italian investigators conducted measurements which included optical and

microstructure profiling and a suite of chemical and biological sampling. A comprehensive report summarizes data and results from both cruises. Calibration and lag corrections for towed profiler measurements are complete and fully processed data sets are available for scientific analysis.

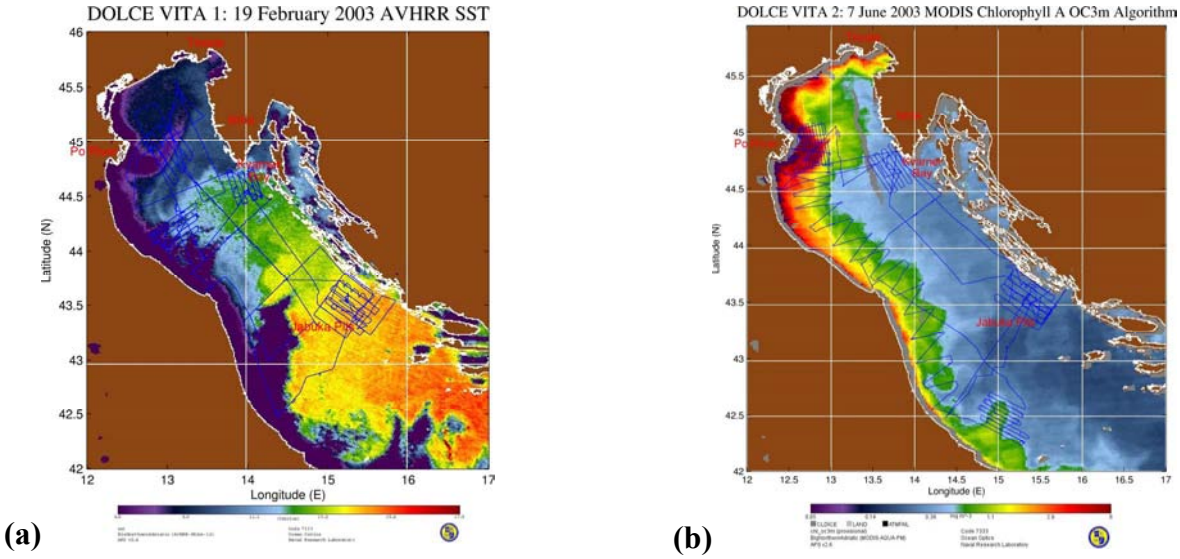


***Figure 3. Remotely sensed (a) AVHRR sea surface temperature (23 February) and (b) SeaWiFS ocean color (7 June) with blue lines marking the survey track.***

The winter (February 2003) field program sampled the response to small-scale Bora wind forcing in the absence of significant riverine buoyancy input. Northeasterly (Bora) winds were present throughout the entire cruise, with a mean wind speed of 7 m/s punctuated by strong events of up to 18 m/s lasting 1-3 days. At the start and end of the cruise, we executed broadscale surveys spanning the region north of the Jabuka Pits (Fig. 3). These were designed to identify dense water formation regions, characterize wintertime variability and provide length scale statistics to aid other analysis. To investigate the relative roles of bathymetric steering and wind forcing, we executed a set of intensive surveys at the northern end of the Jabuka Pit, where the East Adriatic Current (EAC) bifurcates, part flowing westward to follow the bathymetry (forming the Mid-Adriatic Filament (MAF)), with the remainder continuing north along the Croatian coast. A set of nested surveys occupied after a strong Bora event captured the counter-rotating gyres and upwind extension of the Po River plume (Fig. 4) anticipated from numerical results Orlic et al., 1994. These features dominate the northern basin and are hypothesized to be the response to intense, small-scale (O(10 km)) wind stress curl associated with Bora jets passing though the Gulf of Trieste and Kvarner Bay.

In sharp contrast to wintertime conditions, the May/June cruise occurred during a period of extremely weak wind and riverine forcing. In the absence of significant wind-induced mixing, intense surface warming produced very shallow (0-5 m) mixed layers with significant stratification extending throughout the water column. Intensive surveys focused on the MAF, the Istria front, the Po plume bulge and a Po plume instability located well downstream of the inflow region (Fig. 2b). A series of cross-shelf sections extending from the Po delta to the Jabuka Pit documented downstream physical and optical evolution of the Po plume. All surveys exhibited energetic small-scale velocity and T-S variability, with both TriSoarus and drifter measurements suggesting a significant near-inertial component. Even weak winds may have been enough to set the thin surface layer in motion.

Results have been presented in meetings and through publications, with others in preparation. The PI

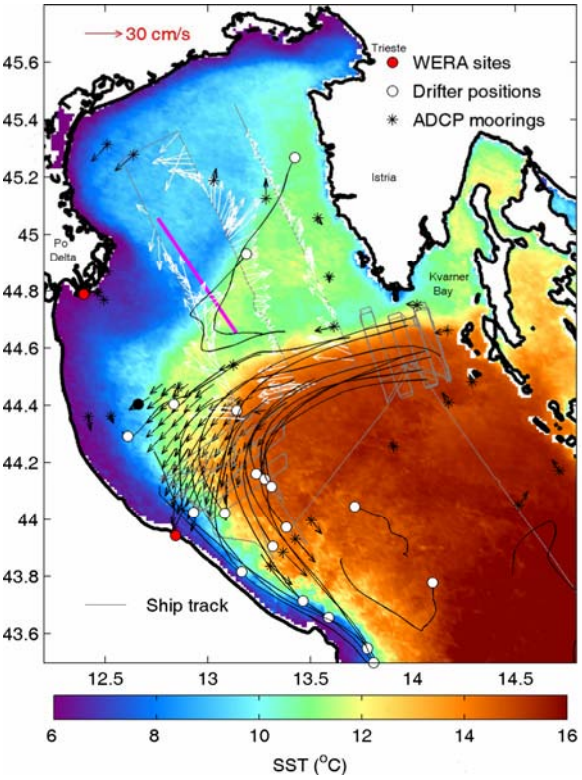


***Figure 4. (from Lee et al. 2005) Nine-day mean AVHRR sea surface temperature with current vectors and drifter tracks illustrating observations collected during the 11-19 February 2003 Bora. Gray lines mark part of the R/V Knorr cruise track, with white arrows showing 12 m velocity measured from the shipboard ADCP. Black lines trace drifter tracks, with white circles marking locations at the end of this period. Black asterisks and arrows indicate near surface, 9-day mean velocities measured by bottom-mounted ADCPs and current meter moorings. The field of black arrows between 44° N and 44.4° N depict the 9-day mean surface velocity field measured by two WERA high-frequency coastal radars (located on the Italian coast at the red circles). Note the paired cyclonic/anticyclonic circulation associated with the Bora forced plume in the Northern Adriatic.***

led the effort to produce an article discussing the recent Adriatic Sea research activity. The resulting paper (Lee et. al., 2005) provides a multi-disciplinary description of the February 2003 Bora event and illustrates the broad scope of measurement and modeling activities. Pierre-Marie Poulain, Mirko Orlic, Benoit Cushman-Roisin and Craig Lee are serving as guest editors for a JGR special section on the Adriatic. Lee has acted as the primary contact with Journal of Geophysical Research editor John Klinck and staff during this process. The special section will appear in two volumes, the first of which is scheduled for print publication in December 2006. Over twenty papers have been submitted to the special section, with several more expected in the coming months. The PI also hosted Marko Pavic, a graduate student currently studying under Mirko Orlic at the University of Zagreb, as a visiting scholar at the Applied Physics Laboratory during summer 2006. Pavic will collaborate on analysis of the extensive towed profiling measurements collected under this project, with the PI joining his supervisory committee at the University of Zagreb..

**RESULTS**

New climatological results and recent measurements reveal two wintertime Northern Adriatic dense water pools situated beneath the strong Bora pathways in the Gulf of Trieste and off of Kvarner Bay. Climatological fields formed by averaging wintertime historical data from time periods during and directly following Bora events (Fig. 5, top row) identify two distinct regions of dense water formation in the Gulf of Trieste and west of Kvarner Bay, both beneath strong Bora wind jets. A region of lighter, less saline waters extends from the Po river delta to separate the two dense water pools. Similar, though less distinct, patterns emerge from the wintertime climatology (Fig. 5, bottom row). Drifter tracks, surface currents, underway ADCP velocities and remotely sensed SST (Fig. 4) taken

during the February 2003 Bora identify paired cyclonic/anticyclonic (north/south) circulation cells in the northern basin, consistent with the modeled response to strong, small-scale windstress curl associated with Bora forcing (Orlic et al. 1994. Both models and observations (Fig. 4) reveal fresh, cold Po river water

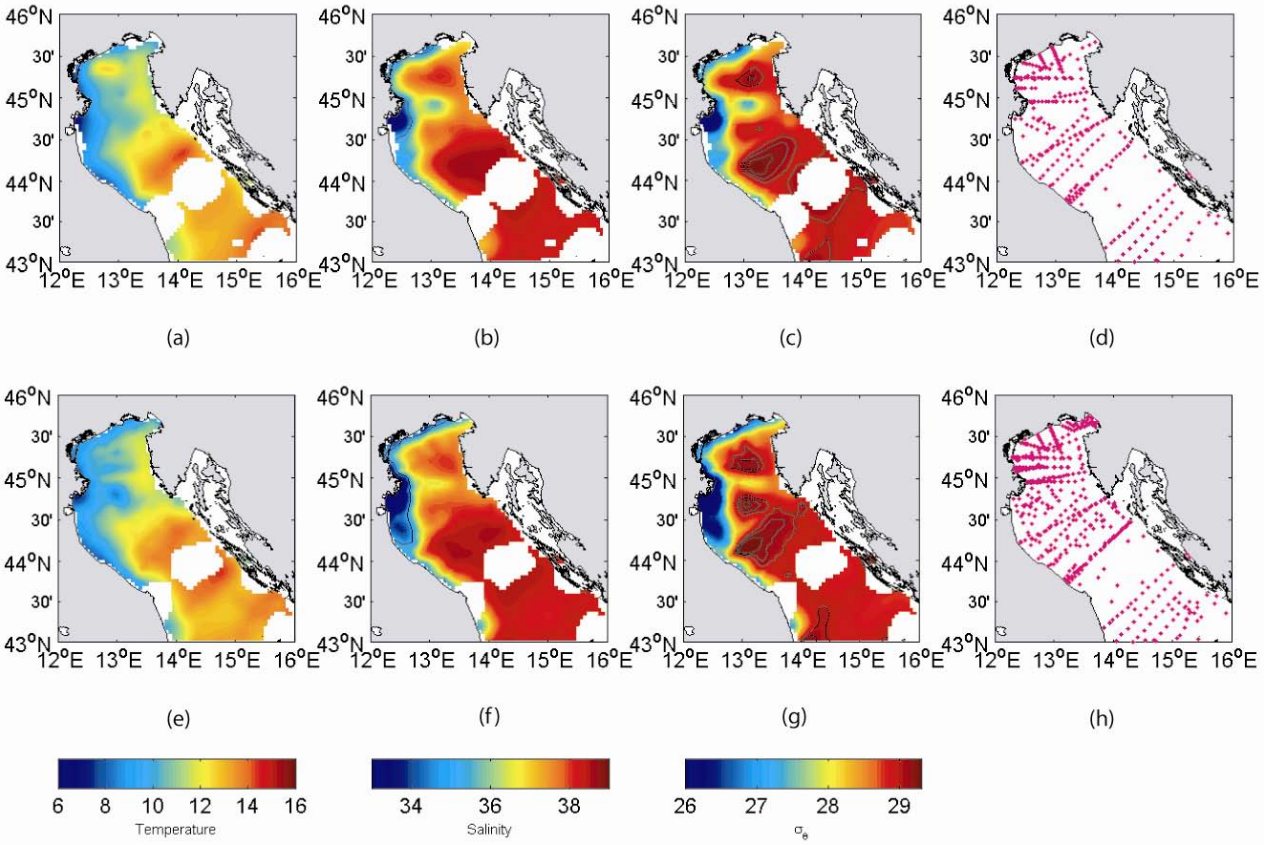


***Figure 5. Climatological surface temperature, salinity and density maps during Bora events (top row) and for the overall wintertime mean (bottom row). Charts in the rightmost column indicate data distribution. The Bora climatology (top row) and, to a lesser degree, the winter maps (bottom row) reveal two distinct dense water pools in the Northern Adriatic separated by a filament of fresh, cold water.***

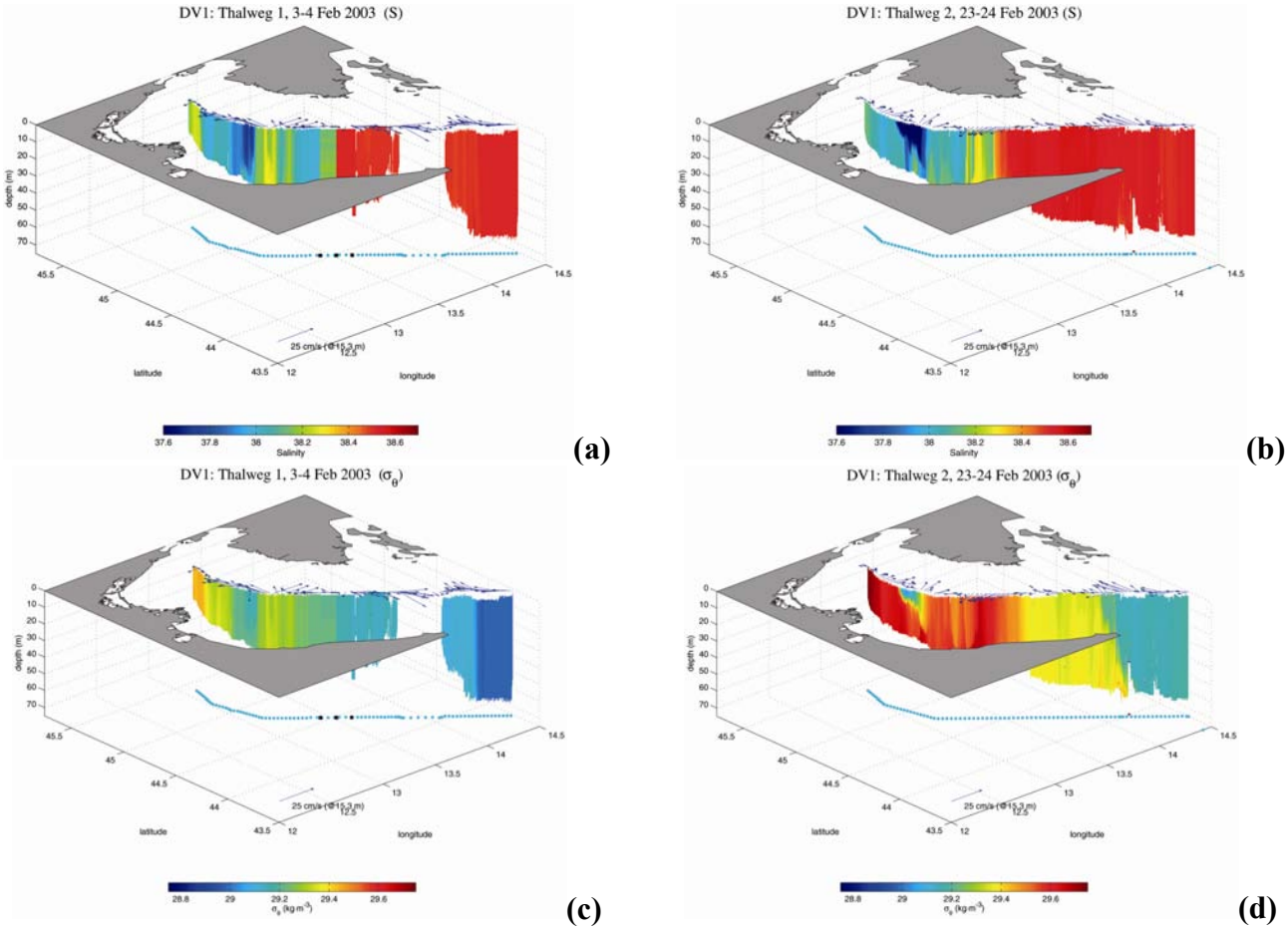


***Figure 6. Along-basin (thalweg) temperature and density sections occupied before (a, c) and after (b, d) the February Bora. Light blue marks indicate profile locations and current vectors are from the 22 m bin of the shipboard ADCP.***

drawn offshore in a narrow filament between the two counter-rotating gyres. Along-basin sections occupied before and after the February Bora show density increasing throughout the northern basin except in a narrow, fresh band formed by the filament of Po water. The depth-integrated change in heat content between the two occupations implies an average net surface heat loss of 100 – 200 W/m2, of similar magnitude to that estimated for the Bora. The separate dense water pools may thus result from two contributing wind-driven processes. Regions of strong (weak) winds drive large (small) net surface heat loss, imparting spatial contrasts in water column density. Small-scale curl associated with Bora events also drives paired cyclonic/anticyclonic circulation which produces a filament of fresh Po River water that extends eastward from the delta. This filament introduces a narrow band of strongly stratified water into the region between the two wind jets, perhaps modulating dense water formation by inhibiting convective overturning.

## IMPACT/APPLICATION

The new hybrid SeaSoar system provides a flexible new platform for making synoptic measurements in both nearshore and open-ocean environments. TriSoarus complements our Triaxus system, with each platform providing distinct capabilities while also acting as a drop-in backup vehicles for each other.

## TRANSITIONS

None.

## RELATED PROJECTS

Shallow Water Climatology and Analysis with Application to the Adriatic Sea, C. Lee (APL-UW)

Optical Dynamics in the Adriatic Sea: The Role of River Plumes, Filaments and Fronts in the Distribution, Advection and Transformation of Inherent and Apparent Optical Properties, B. Jones (USC).

Adriatic Mesoscale Experiment, P. Poulain (OGS- Trieste).

East Adriatic Coastal Experiment (EACE), M. Orlic (Univ. of Zagreb).

Mesoscale Dynamics of the Adriatic Sea, B. Cushman-Roisin (Dartmouth).

Surface Current Maps from High Frequency Radar, P. Flament (U.H.) and P. Poulain (OGS-Trieste)

The Adriatic Circulation Experiment, H, Perkins (NRL-Stennis), J. Miller (NRL- STennis) and R. Signell (SACLANTCEN).

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